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FIELD AND COMPUTER SIMULATION EXPERIMENTS ON THE FORMATION OF DESERT PAVEMENT

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ABSTRACT

A series of rainfall simulation experiments was carried out at the Walnut Gulch Experimental Watershed, Tombstone, Arizona (31° 43′N, 110° 41′W), to observe the speed at which desert pavement surfaces could be re-established following disturbance. The results of these experiments, which consisted of repeated, 5 min rainfall events, demonstrate that pavements can reform within 10 events, which is compatible with observations of the recovery of surfaces under natural rainfall on an annual cycle. A model for the development of pavements by raindrop erosion processes had previously shown the importance of these processes. The rainfall simulation experiments were used to test the general applicability of this model. The model was able to reproduce the general characteristics of the regenerated surfaces and the timing of their development. However, details of the particle size fractions produced were less well simulated by the model. Testing of the sensitivity of the model to the sediment transport parameters suggests that this problem is not related to the soil characteristics, but is more likely to be an indication of a poor understanding of all the feedbacks operating in the raindrop erosion processes. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: raindrop erosion; desert pavement; simulation model; differential erosion rates; rainfall simulation

INTRODUCTION

In a previous paper (Wainwright *et al.*, 1994), the formation of desert pavement was examined using a simulation model. This model showed that raindrop erosion processes can contribute to the formation of desert pavement. Comparison of the model output with field data taken from a shrubland vegetation community within the Walnut Gulch Experimental Watershed, Tombstone, southern Arizona (31° 43′N, 110° 41′W), revealed that, although the model successfully predicted the observed accumulation of fines beneath the shrubs, the concentration of coarse particles in the intershrub areas was underpredicted by the model. However, because the only comparisons that could be made were between observed surface conditions and end-point predictions of the model, no explanation for the underprediction could be obtained.

A second weakness of the testing of the simulation model as presented in Wainwright *et al.* (1994) was the inability to test the timescale for the rate of pavement formation by raindrop erosion processes. The model suggested that pavement could form by these processes after only one storm of 20 min duration at an intensity of 44 mm h^{-1}. From a practical point of view this is an important suggestion. There is increasing need for understanding rates of recovery of pavement surfaces which have been disturbed, particularly because the use of such areas is increasing (Wilshire, 1980; Gillette and Adams, 1983), and because these rates have implications for problems of blowing dust (Péwé, 1981; Middleton, 1990). Our own preliminary field observations lend qualitative support to the modelling results. Surfaces that have been disturbed without removal of coarse material have been observed to regenerate within a period of a year. In the case of Walnut

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Gulch, the average number of runoff events per year at a point is between 10 and 12 (Osborne, 1983). Therefore, a relatively small number of rainfall events seem to lead to this regeneration.

The present study was designed to address both of the above issues. A series of field experiments was carried out to observe the rates of recovery of disturbed desert pavement surfaces. The results of these field simulations were then compared with numerical simulations to check the extent to which the simulation model of Wainwright *et al.* (1994) reproduces the effects of raindrop erosion. These methods can be used to test our understanding of the operation of this process. In this paper, desert pavement will be taken to mean any paved or armoured slope surface.

FIELD SIMULATION OF DESERT PAVEMENT

The computer simulations (Wainwright *et al.*, 1994) suggested that there is a sensitivity to initial conditions in the development of pavements under raindrop erosion processes. Consequently, sites with contrasting pavement surfaces were chosen for the field experiments. Three such sites were identified within the Walnut Gulch Experimental Watershed (Figure 1). All three plots were dominated by a coarse surface layer, with sediment of granular size (2–12 mm) being dominant in all cases (Table I). However, plot 3 was dominated by this class (67 per cent) whereas plot 2 had more even proportions of this class (39 per cent) and the coarsest class of > 12 mm (31 per cent). Plot 1 had a particle-size distribution between those of plots 2 and 3. The importance of the granular fraction which is mobile under the action of raindrop erosion processes implies that these pavement surfaces were partly composed of a dynamic armour layer, in distinction to those of a coarser texture (see, for example, Haff and Werner, 1996).

To remove the effects of variability due to other factors, all three sites were chosen on similar, planar slopes of about 1°. At each of the sites an area $2{\cdot}5 \times 2{\cdot}5$ m was marked out. This area was made up of a central zone of $0{\cdot}5 \times 0{\cdot}5$ m, in which measurements were made, and a buffer zone of 1 m around each edge. The initial characteristics of the pavement surface were measured using a point sampling technique by laying out 10 transects in the central area and noting the surface particle size at 5 cm intervals. Thus, 100 points were sampled to characterize the surface particle-size distribution. All transect measurements were taken from a small ‘bridge’, so that the surface would not be disturbed. The whole plot was dug out to a depth of approximately 10 cm, the soil placed in a container and mixed thoroughly. The soil was then replaced on the plot, taking care to retain a level surface without compacting it or causing the larger particles to return to the surface. At this point, the transects were replaced and the surface cover measured again. The effectiveness of this mixing can be seen by the differences in particle-size distributions before and after mixing (Table I). It should be noted that, as the purpose of the study was to observe the development of the surface after disturbance, no material was removed. The procedure outlined above simply mixes the coarse particles which are concentrated at the surface with the horizon dominated by fines that usually underlies the pavement surface, usually due to a process of aeolian accretion. The particle-size data imply that the subsurface horizon is dominated by the fraction $< 0{\cdot}125$ mm, which is consistent with an aeolian source for this sediment. The vesicular texture and low bulk density of the subsurface soil allowed the mixed sediment to be replaced flush with the surrounding surface.

A series of rainfall simulation experiments was then carried out on each of the plots, using the rainfall simulator described by Luk *et al.* (1986). The buffer zone is used so that boundary conditions are not important in controlling the processes on the measurement area. Less material could potentially be transported into the measurement zone than transported out if it were immediately adjacent to a pavement surface from which the fine component had already been removed. The buffer zone therefore acted to prevent the pavement surfaces from developing more rapidly than they otherwise should. Ten 5 min rainfall simulations, each at an intensity of $73{\cdot}2$ mm h^{-1}, were carried out on the three plots. These intensities and durations are characteristic of the convective storms which dominate the rainfall in the area, although for experimental convenience, the interval between them was much reduced. At the end of each 5 min experiment, the rainfall was stopped and the transects replaced so that the surface cover could be remeasured. Because the model produces results with more closely defined size classes than can be measured by the point-sampling technique, surface soil samples were collected for laboratory particle size analysis before and after

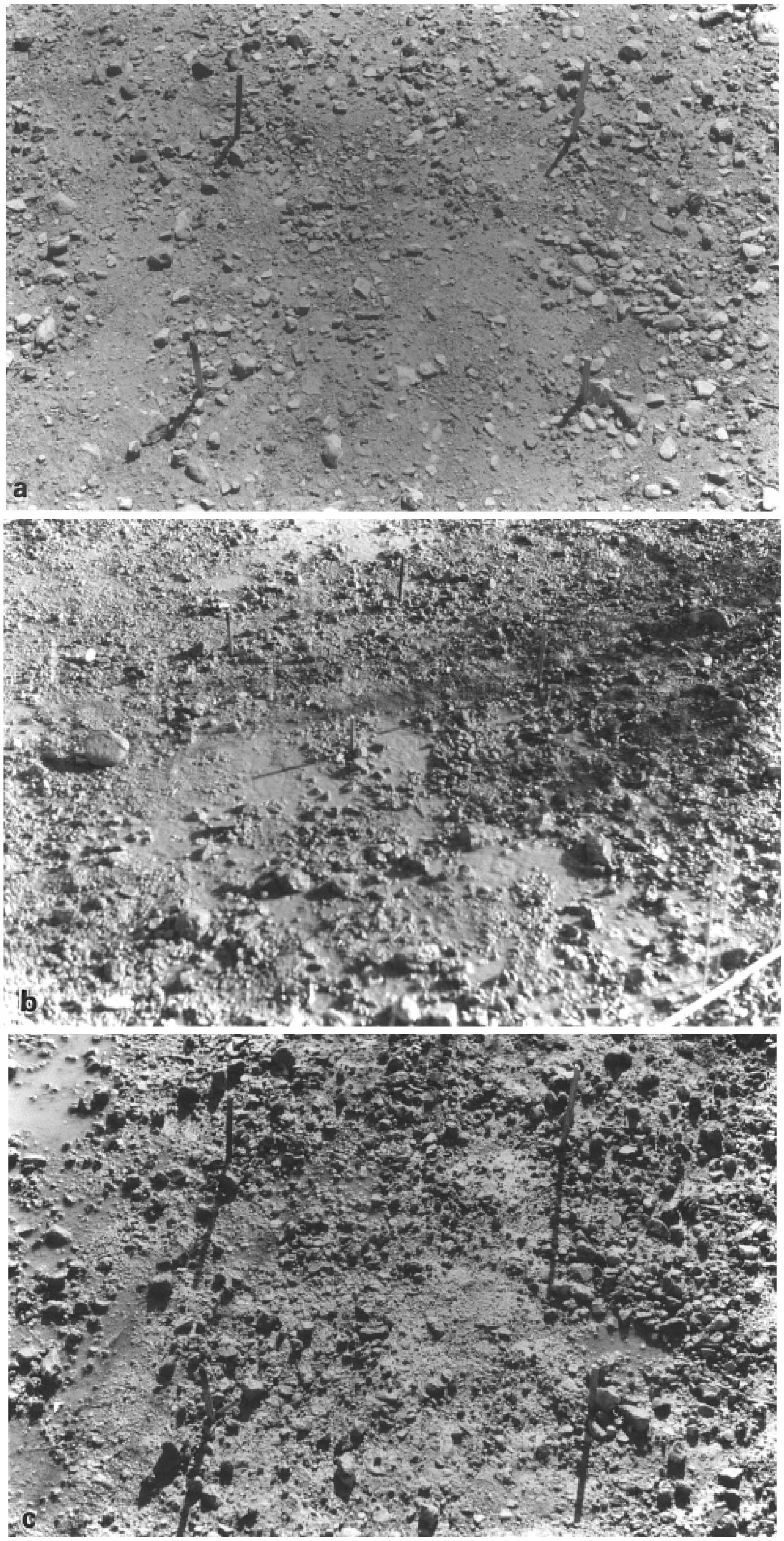


Figure 1. Example of pavement surface used in the rainfall simulation experiments: (a) following disturbance; (b) during fifth simulated event (note runoff); (c) after 10 simulated events. The area marked out by the vertical stakes is 0·5 m × 0·5 m in each case

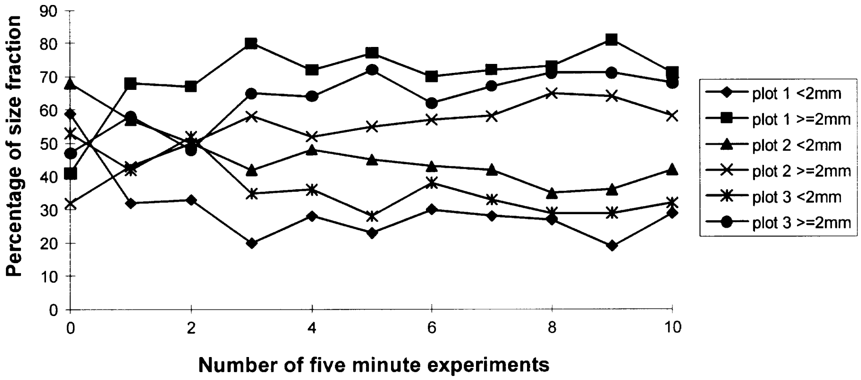


Figure 2. Evolution of surface conditions on three disturbed desert pavement plots at Walnut Gulch during 10 consecutive, 5 min rainfall simulation experiments

the surface was disturbed and after the completion of the rainfall simulations. These samples were obtained by scraping the surface layer with a small trowel. The measured quantities of fines within these samples were then scaled according to the measurements from the transects. No other measurements of flow or sediment transport were undertaken during the experiments in order to minimize the disturbance to the developing surface.

The results of these rainfall simulation experiments demonstrate that the pavement surface does indeed develop rapidly under rainfall (Figures 1 and 2). Using the percentage stone cover (particles ≥ 2 mm) as an indication of the extent of pavement development, on plot 1 the stone cover of 41 per cent on the freshly disturbed surface increases to 71 per cent by the end of the ten 5 min rainfall events. The final stone cover compares well with an initial stone cover of 77 per cent. For plot 2 the increase is from 32 to 65 per cent after eight simulated events, although there is a subsequent decrease to 58 per cent after the tenth event, in comparison with the original surface cover of 70 per cent. After the fifth event on plot 3, the stone cover has increased from 47 to 72 per cent, compared to the initial stove cover of 84 per cent. The stone cover oscillates between 62 and 71 per cent during the remaining five events. However, it is likely that these oscillations were due to measurement errors, as all the oscillations fall within 5 per cent of a moving average through the data.

Table I. Comparison of percentage of surface size classes before and after disturbance, and following 10 rainfall simulation experiments for three experimental plots at Walnut Gulch

	Particle size class (mm)					
Sample	<0·063	0·063–0·125	0·125–1·0	1·0–2·0	2·0–12·0	>12·0
Plot 1 original surface*	–	–	–	–	–	–
Plot 1 disturbed	12·43	31·57	8·66	6·25	29·52	11·52
Plot 1 after simulations	10·27	7·24	3·60	7·89	49·00	22·00
Plot 2 original surface	14·95	8·52	2·24	4·28	39·00	31·00
Plot 2 disturbed	18·66	24·18	9·65	15·50	20·00	12·00
Plot 2 after simulations	14·24	13·54	5·14	9·08	40·00	18·00
Plot 3 original surface	2·71	3·94	2·11	7·25	67·00	17·00
Plot 3 disturbed	22·51	14·53	4·64	11·32	40·00	7·00
Plot 3 after simulations	10·51	10·49	3·81	7·19	53·00	15·00

* Sample lost

These experiments are consistent with the observation that the pavement surfaces do regenerate rapidly after disturbance. To test whether the computer simulation model of Wainwright *et al.* (1994) is capable of reproducing both these rates, and the final stone cover, the model was applied to the data derived from each of the three plots.

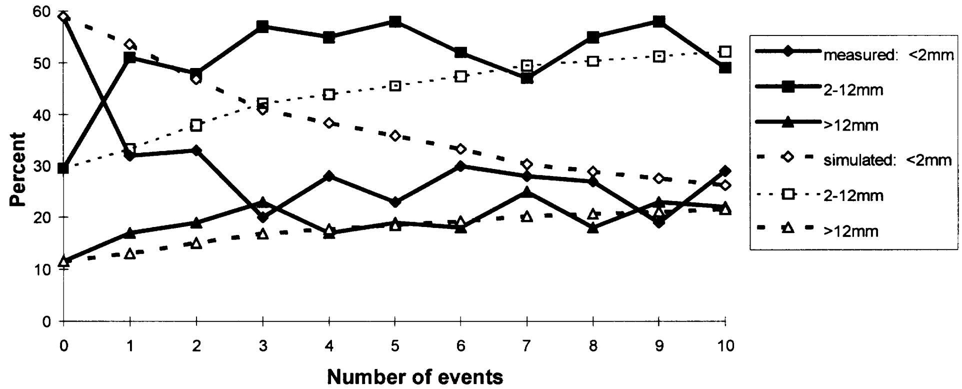
TESTING THE MODEL OF DESERT PAVEMENT FORMATION

Wainwright *et al.* (1994) developed a simulation model of the differential effects of raindrop erosion processes on surface particle transport. This model divides the surface soil into six size categories (i.e. $< 0{\cdot}063$ mm, $0{\cdot}063$ to $< 0{\cdot}125$ mm, $0{\cdot}125$ to $< 1{\cdot}0$ mm, $1{\cdot}0$ to $< 2{\cdot}0$ mm, $2{\cdot}0$ to $< 12{\cdot}0$ mm and ≥ 12 mm) and calculates the effects of raindrop erosion on each category. The need for data to parameterize the model according to these size classes limits the available components for the model. A full description and justification of the model form and equations used are given in Wainwright *et al.* (1994). The erosion processes considered are splash, raindrop detachment and transport in overland flow. Rainfall impacting on a soil surface causes transport of sediment by splash. The amount of material splashed is determined using experimental data of Quansah (1981) and Wainwright (1991), which show that splash is a function of particle size, kinetic energy and slope. Infiltration rates are calculated using the simplified Green and Ampt model. Overland flow is generated using a Hortonian model once the infiltration rate decreases below the rainfall rate and then routed across the surface using a hydraulic model developed for sites in the field area under study (Scoging *et al.*, 1992; Parsons *et al.*, 1997; Wainwright and Parsons, 1998). As overland flow causes the depth of water to build up, the rate of detachment of sediment by raindrops decreases exponentially, according to the model of Torri *et al.* (1987). This sediment is transported by the overland flow, with transport distance defined using a gamma distribution function whose parameters again depend on grain size (Wainwright, 1991; Hubbel and Sayre, 1964; Grigg, 1970; Yang and Sayre, 1971).

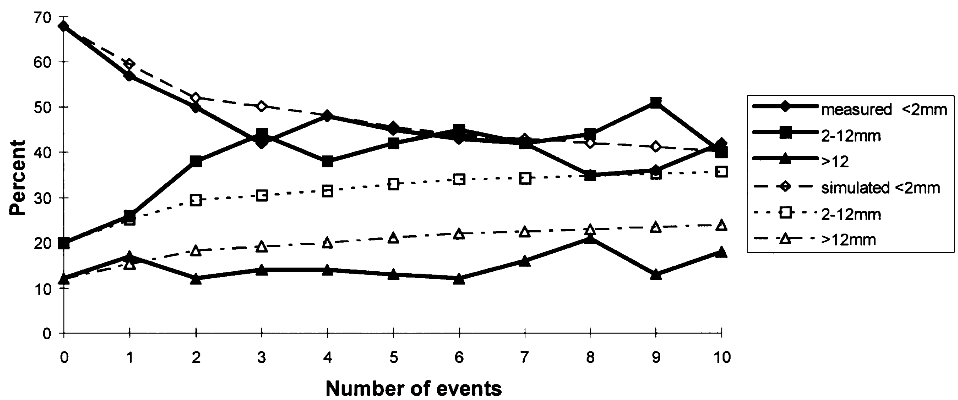
The model was tested by applying it to the initial conditions of the field experiments (i.e. the particle-size distribution of the disturbed surface) and comparing the measured and simulated development of pavement under rainfall. The model is the same as reported previously, with the exception that the kinetic energy used to calculate rates of splash is defined directly as the measured kinetic energy for the rainfall simulator used in the field experiments (Luk *et al.*, 1986), rather than using a relationship dependent on rainfall intensity. In these experiments, a model cell size of $0{\cdot}5$ m $\times$ $0{\cdot}5$ m was used, with a simulated area of 10 by 10 cells. To remove the edge effects from the model, only the central 25 cells have been employed for comparative purposes, using an average of the particle size characteristics of these cells.

Because the point-sample data do not resolve the six size classes used in the model, evolution of the surface is evaluated by comparing the percentages of fine (<2 mm), medium (2–12 mm) and coarse ($\geq$12 mm) particles. The results show that the model produces pavement at approximately the same rate as was measured in the rainfall simulation experiments (Figure 3). After 10 experiments, the three simulated percentages for plot 1 are 26·2, 52·2 and 21·6 per cent, which compare very closely with the measured values of 29, 49 and 22 per cent, respectively. In the case of plots 2 and 3, there is a slightly greater discrepancy, but the values are still relatively close. The simulated values for plot 2 are 40·3, 35·7 and 24·0 per cent compared with measured values of 42, 40 and 18 per cent, respectively. For plot 3, the two sets of values are 37·7, 52·7 and 9·6 per cent (simulated) and 32, 53 and 15 per cent (measured). However, there are differences in the ways in which the three plots reach their final states. The experimental surfaces changed much more rapidly than predicted by the model for plot 1, whereas plots 2 and 3 are quite well predicted for the first two or three events. The model then tends to overestimate the coarsest (>12 mm) fraction on plot 2, but to underestimate it for plot 3. These differences are compensated in plot 2 by a slight underestimation of the 2–12 mm range, and in plot 3 by an overestimation of the < 2 mm fraction. In addition, if the model is allowed to continue to run for 75 events, surfaces are predicted that are made up almost entirely of the three coarsest model sizes (>1 mm). These surfaces are much coarser than the original pavement surfaces (and bear a qualitative resemblance at least to the interlocking pavements found on the alluvial fans of Death Valley, California; see also Haff and Werner (1996) on similar surfaces in Panamint Valley, California). This result seems to indicate that at Walnut Gulch, other processes presumably interrupt the development of surfaces by raindrop erosion processes. Observation

Plot 1



Plot 2



Plot 3

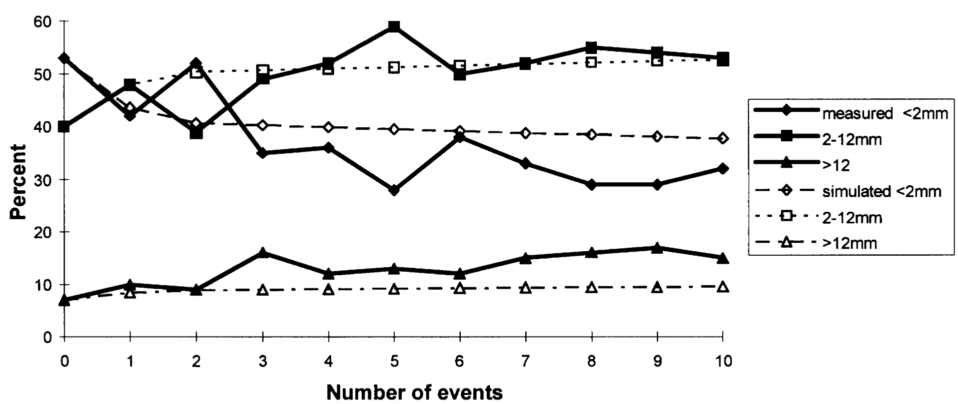


Figure 3. Comparison of rainfall simulation results with model simulations on three disturbed desert pavement plots at Walnut Gulch during 10 consecutive, 5 min rainfall simulation experiments

Table II. Comparison of percentage of surface size classes following ten 5 min events between the field experiments and the computer simulations for the three experimental plots

Sample	Particle size class (mm)					
	<0·063	0·063–0·125	0·125–1·0	1·0–2·0	2·0–12·0	>12·0
Plot 1 measured	10·27	7·24	3·60	7·89	49·00	22·00
Plot 1 simulated	0·00	15·46	0·00	10·77	52·21	21·56
Plot 2 measured	14·24	13·54	5·14	9·08	40·00	18·00
Plot 2 simulated	9·76	0·00	0·00	30·50	35·69	24·04
Plot 3 measured	10·51	10·49	3·81	7·19	53·00	15·00
Plot 3 simulated	22·57	0·00	0·00	15·14	52·69	9·61

of the development of vesicular subsurface horizons after winter when rain is scant and of insufficient energy to cause runoff suggest that the dominant process is likely to be the action of winter frost (see Mabbutt, 1977).

A comparison of the six particle size classes for the experimental plots and model simulations at the end of 10 experiments (Table II) indicates that the model performs less well at this more detailed level of resolution. Although, as seen above, there is a good replication of the two coarse size classes, the model performs relatively poorly in the simulation of the development of the finer size classes. In particular, there is a tendency for two of the four fine size classes to decline effectively to zero (size classes $< 0{\cdot}063$ mm and $0{\cdot}125$ to $< 1{\cdot}0$ mm for plot 1; size classes $0{\cdot}063$ to $< 0{\cdot}125$ mm and $0{\cdot}125$ to $< 1{\cdot}0$ mm for plots 2 and 3), which leads to an effective over-representation of the two remaining size classes. This overrepresentation is seen particularly with size class $1{\cdot}0$ to $< 2{\cdot}0$ mm on each of the three plots. It is possible that these problems reflect the fact that the model does not incorporate the effects of the presence of particle aggregates, which could affect the size ranges available for transport and reduce the transport of the finer particle-size classes. Correspondingly, the model does not incorporate the dynamic effects of particle aggregation and disaggregation during a rainfall event.

A relatively simple means of testing whether these inaccuracies in the simulation of the evolution of the finer size classes are a function of the model formulation of the sediment-transport process, is to calibrate the particle movement parameters to determine whether a better fit is obtainable. If the calibration procedure were successful, it would suggest that a possible reason for the inaccuracies was that parameterization of the model from the literature was based on different soils from those found at Walnut Gulch. If not, there would be a strong suggestion that there are one or more missing elements or feedbacks that should be considered within the model. An alternative explanation is that the parameters should, in fact, be variables that are a function of the mix of grain sizes, and therefore should continuously evolve. However, such a complex understanding of the relationships between the parameters and surface conditions is unfortunately not available at present, so that this alternative explanation is not testable based on available data.

The calibration procedure used involved modifying the three parameters (*a, b* and *c*) in the detachment equation (Quansah, 1980):

$$q_{sp} = aKE^b S^c \tag{1}$$

where q_{sp} is the raindrop detachment rate (kg m^{-2} s^{-1}), KE is the rainfall kinetic energy (J m^{-2}) and S is the surface slope (m m^{-1}). The decision to focus on the calibration of the detachment equation was made because detachment by raindrops is the dominant mechanism of sediment mobilization in interrill overland flow (Parsons and Abrahams, 1992; Govers and Poesen, 1988; Wainwright, 1996a, b). The parameters were modified initially over a range of an order of magnitude above and below the literature values and optimized for each parameter to produce the best fit against the experimental data for each of the four finest size ranges. Best-fit values of each of the parameters were used and modified slightly to provide the best fit for all parameters being modified at the same time. The original and modified parameters are presented in Table III.

A series of repeated, 5 min simulated storms was carried out using the optimized parameters (Figure 4). The results of these simulations are presented in Table IV. They illustrate that, although in certain cases there

Table III. Comparison between detachment parameters for Equation 1 derived from the literature (see Wainwright *et al.*, 1994) and optimized for the Walnut Gulch soils

Size class (mm)	*a*		*b*		*c*	
	Literature	Optimized	Literature	Optimized	Literature	Optimized
<0·063	$1{\cdot}0 \times 10^{-5}$	$5{\cdot}0 \times 10^{-6}$	1·35	1·24	0·27	0·23
0·063–0·125	$3{\cdot}0 \times 10^{-4}$	$9{\cdot}5 \times 10^{-5}$	1·16	1·08	0·25	0·21
0·125–1·0	$3{\cdot}0 \times 10^{-4}$	$6{\cdot}0 \times 10^{-5}$	0·84	0·79	0·13	0·11
1·0–2·0	$2{\cdot}0 \times 10^{-4}$	$9{\cdot}5 \times 10^{-5}$	1·06	1·14	1·03	1·06

are improvements, these are by no means consistent across the three experimental plots for individual size classes. Plots 2 and 3 show distinct improvements in the goodness of fit for size classes 2 and 3. However, on these plots the two coarsest size classes are slightly less well reproduced than with the original parameters. On plot 1, there is also an improvement with the prediction of size class 3, albeit with a deterioration in the results for classes 2 and 5. There still remain four cases in the experiments where one of the fine size classes is reduced to zero by the end of the series of 10 simulated events. If the model is allowed to continue for 75 events, the reduction to zero is still apparent in the five size classes that were affected in the original model runs.

A further means of comparison and calibration is to observe the predictions of splash-transport rates predicted by the model. As noted above, splash rates were not measured directly on the experimental surfaces so as not to disturb the regeneration of the surface. However, measurements made by Parsons *et al.* (1991) on similar soils in the Walnut Gulch catchment produced a rate of 0·432 g $m^{-2}min^{-1}$ for a well established pavement. The rate during the tenth 5 min simulated event should approach this value given that the surface covers are similar. Using the original parameter set, the estimate rates decline from 0·225 g $m^{-2}min^{-1}$ in minute 1 of the event to 0·078 g $m^{-2}min^{-1}$ in minute 5 for plot 1. Plots 2 and 3 both produce the same rates, decreasing from 0·223 to 0·078 g $m^{-2}min^{-1}$. It is interesting that using the optimized parameter set, although the surface characteristics evolve differently, there is little difference in the rates produced (0·222 to 0·078 g $m^{-2}min^{-1}$ for plot 1, 0·225 to 0·078 g $m^{-2}min^{-1}$ for plot 2, and 0·224 to 0·078 g $m^{-2}min^{-1}$ for plot 3 in the tenth event). This result suggests that the splash rate is relatively insensitive to the parameters of Equation 1, probably due to the interactions between the different particle-size classes being moved and the relatively rapid development of overland flow which provides protection for the surface against splash. It should be noted that although the rates are very similar in the above cases, the particle-size distributions of the sediment transported differ between the plots. To investigate this sensitivity further, a second calibration was carried out by modifying the parameter *a* in Equation 1 to see whether rates approaching the measured value could be obtained. Simply changing one of the three parameters can be justified because the slope and kinetic energy terms are held constant during the simulated event. The best fit for all three plots was obtained by using large changes in the *a* parameter: from $5{\cdot}0 \times 10^{-6}$ to $1{\cdot}0 \times 10^{-4}$ for particles $< 0{\cdot}063$ mm, from $9{\cdot}5 \times 10^{-5}$ to $6{\cdot}25 \times 10^{-3}$ for particles of 0·063–0·125 mm, from $6{\cdot}0 \times 10^{-5}$ to $4{\cdot}0 \times 10^{-3}$ for particles of 0·125–1·0 mm and from $9{\cdot}5 \times 10^{-5}$ to $9{\cdot}5 \times 10^{-4}$ for particles of 1·0–2·0 mm. These changes produced estimated rates in the tenth event from 0·425 to 0·263 g $m^{-2}min^{-1}$ for plot 1, 0·457 to 0·257 g $m^{-2}min^{-1}$ for plot 2, and 0·430 to 0·260 g $m^{-2}min^{-1}$ for plot 3. However, despite the close fit in terms of the splash rate, there is a much poorer fit in terms of the rate of surface evolution (Figure 5). The surface cover evolves far too rapidly in all cases, and only in the case of the 2–12 mm class for plot 2 and the >12 mm class for plot 3 are good final predictions achieved. Analysis of the evolution of the splash rates through time (Figure 6) demonstrates that the initial rapid development relates to the large increase in the splash rates in the early parts of the first three rainfall events, before overland flow begins to provide protection for the surface. This observation implies that the parameters for Equation 1 may indeed need to be made variable through time.

These results suggest that the calibration procedure was not entirely successful, and that there may be some feedback in operation that is not yet being captured by the model. One such mechanism that was observed qualitatively in the field and during the rainfall simulation experiments was the tendency of grains up to

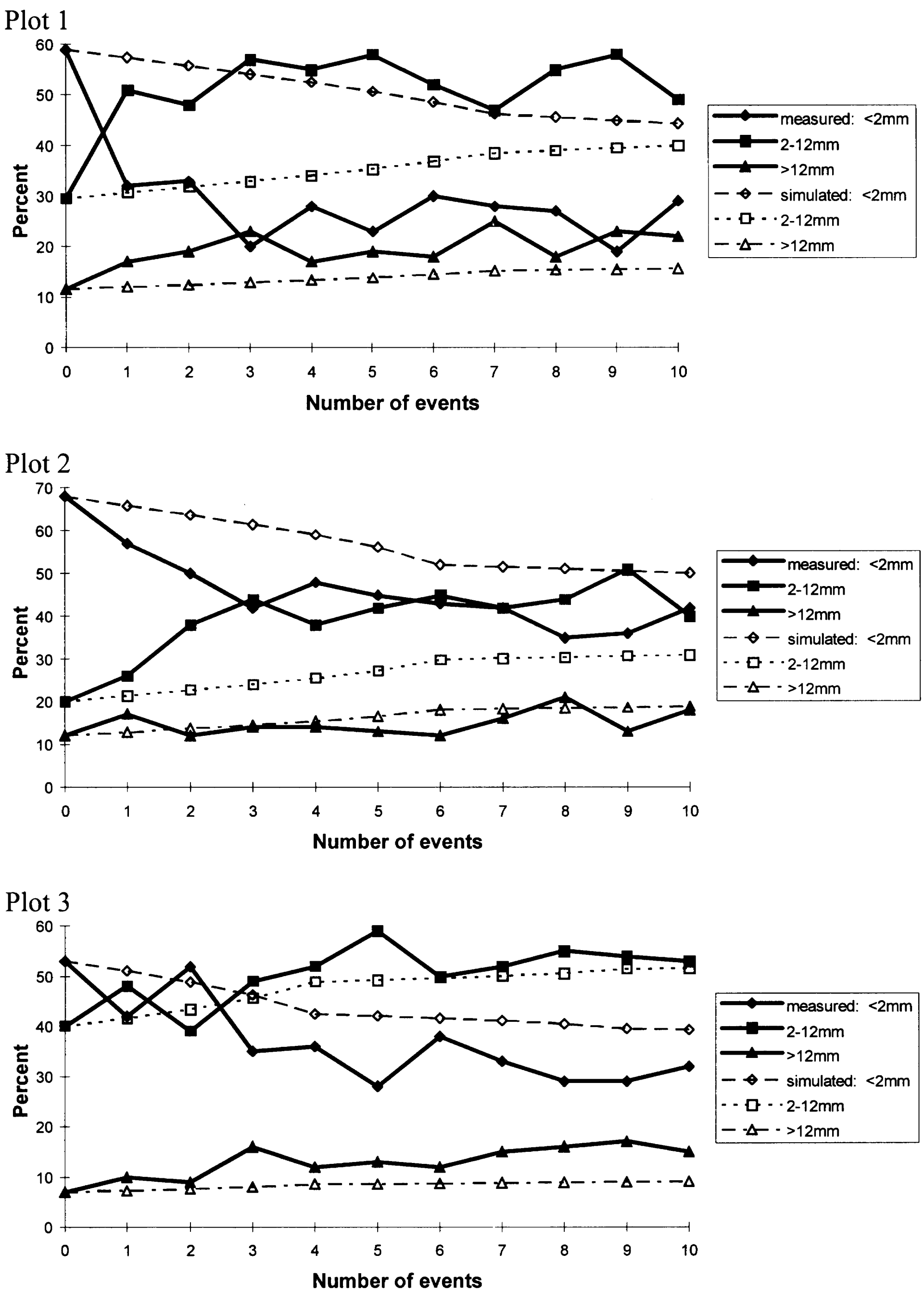


Figure 4. Comparison of rainfall simulation results with model simulations using optimized detachment parameters on three disturbed desert pavement plots at Walnut Gulch during 10 consecutive, 5 min rainfall simulation experiments

Table IV. Comparison of percentage of surface size classes following ten 5 min events between the field experiments and the computer simulations for the three experimental plots using optimized detachment parameters

Sample	Particle size class (mm)					
	<0·063	0·063–0·125	0·125–1·0	1·0–2·0	2·0–12·0	>12·0
Plot 1 measured	10·27	7·24	3·60	7·89	49·00	22·00
Plot 1 simulated	0·00	28·52	8·66	7·13	40·00	15·70
Plot 2 measured	14·24	13·54	5·14	9·08	40·00	18·00
Plot 2 simulated	15·79	0·00	10·89	23·52	31·00	18·81
Plot 3 measured	10·51	10·49	3·81	7·19	53·00	15·00
Plot 3 simulated	25·13	0·00	0·00	14·21	51·60	9·07

granule size to be trapped in small hollows, preventing their further movement. This observation suggests that microtopography is an important component in simulating particle movement, although its incorporation into the present model would be a very time-consuming exercise. Another observation is that if the oscillation about a general trend observed in the field measurements (Figure 3) is real rather than an artefact of measurement error, then this oscillation is not reproduced by the model which produces a steadily changing surface particle-size distribution,. Again, there may be a suggestion that either there are feedbacks which are not captured by the model, or there are stochastic elements within the particle transport which could be incorporated into the model but which are not present in its current, time-averaged form (cf. Wainwright, 1991; Wainwright and Thornes, 1991). There is also the possibility that model parameters representing splash detachment and transport may be dynamic through time due to particle aggregation and disaggregation, as discussed above.

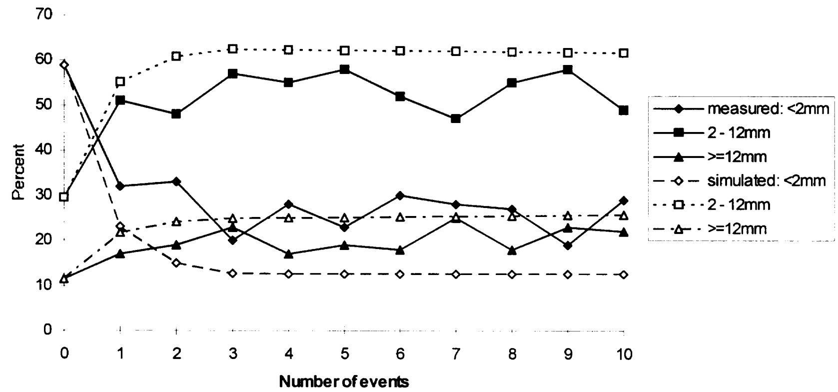
CONCLUSIONS

This study has demonstrated by the use of rainfall simulation experiments that the recovery due to raindrop erosion processes of desert pavement surfaces following disturbance can be extremely rapid. In all three experiments, significant accumulations of coarse particles formed within five 5 min events following the disturbance. Given that more than five such events typically occur every year at Walnut Gulch, pavements can generally be expected to recover on an annual cycle after disturbance.

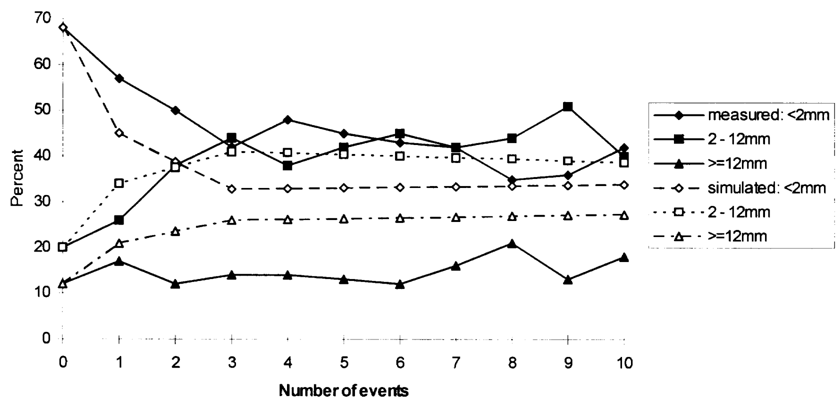
This finding has important consequences for the understanding of the regeneration and management of desert pavement areas, particularly as they affect practical issues such as the control of blowing dust (e.g. Péwé, 1981). The finding stands in contrast to previous studies (e.g. Cooke, 1970; Haff and Werner, 1996) which have suggested that much longer time periods are required for recovery. However, these earlier studies removed the coarse fragments from the surface rather than mixing the surface layer. Such an experimental design is consistent with the original formation of desert pavement surfaces, but not their recovery from disturbance.

Raindrop erosion processes have been demonstrated both experimentally and theoretically to have a significant role in the formation of desert pavements. The present study also serves to illustrate the shortcomings in our understanding of the raindrop erosion processes. The simulation model reproduces the results of the field experiments reasonably well, although it overestimated the movement of finer particles. This overestimate contrasts with the simulations of Wainwright *et al.* (1994) where the development of pavement surfaces was less than that observed, possibly pointing to difficulties in the parameterization of the original surface. The weaknesses appear to be due to the incomplete description of feedbacks within the model, and also to possible deficiencies in the model representation of microtopography. Further research into particle transport is required to resolve these issues. The results of the two calibrations presented here also demonstrate a wider issue relating to model development and validation, in that the calibrations based on separate measures provide results which confirm the model performance with respect to that measure, but not

Plot 1



Plot 2



Plot 3

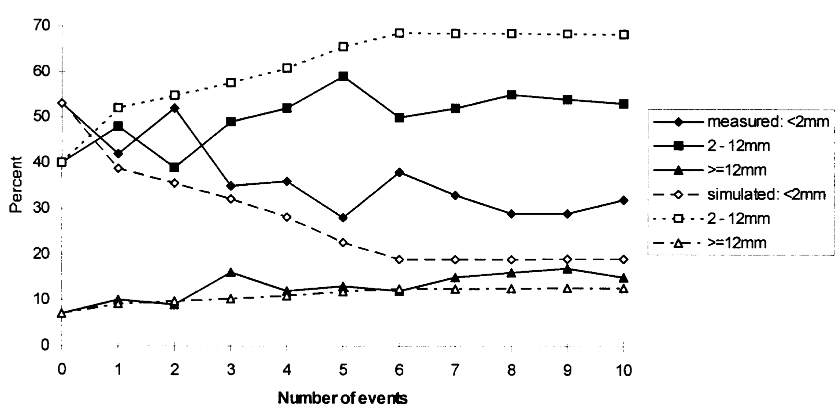


Figure 5. Comparison of rainfall simulation results with model simulations using optimized detachment parameters calibrated to reproduce measured splash rates on three disturbed desert pavement plots at Walnut Gulch during 10 consecutive, 5 min rainfall simulation experiments

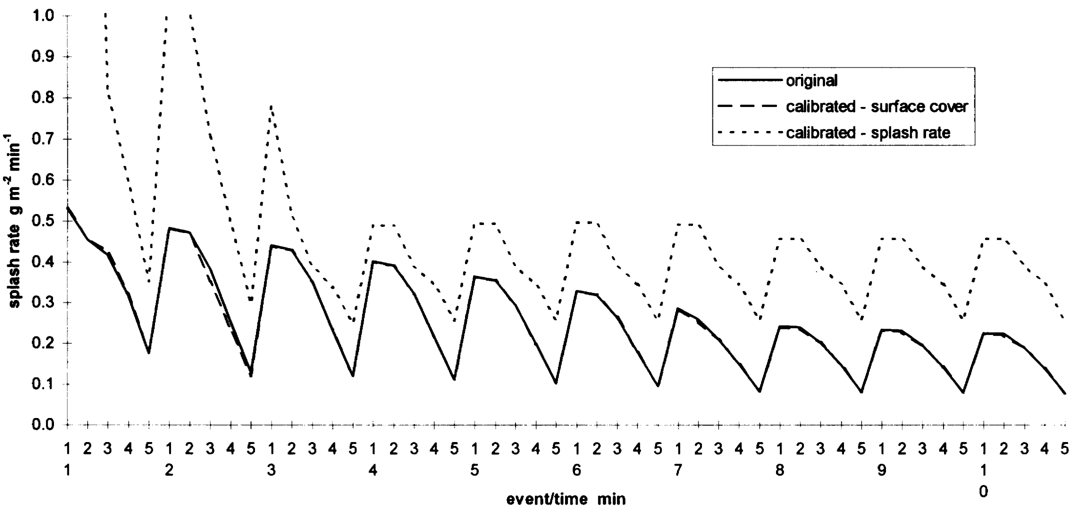


Figure 6. Evolution of splash rates through time for plot 2 using the original parameter set, the optimized parameter set, and the optimized parameter set calibrated to reproduce measured splash rates. Note that the first two of these parameter sets produce very similar results

necessarily to the other. Model testing which ignores the full range of data available for validation is thus likely to produce overoptimistic statements about the performance of the model.

Although the results from the field experiments suggest that raindrop erosion processes are significant in the regeneration of pavement surfaces, the simulation experiments suggest that our understanding of these processes is still limited, particularly at the level of understanding changes relating to particle-size data. A number of erosion models attempt to account for the effects of changing particle size on erosion rates, and the results presented here suggest that if such models are to be more successful than they are at present, more empirical work needs to be undertaken to understand a number of feedback processes in operation. For this reason, we have not simply attempted to produce a calibration of the present model to provide the best fit to the data. To do so would be meaningless in that it tells us nothing further about the processes in operation. The important result, however, is to demonstrate the role that numerical modelling can play in defining problems with our understanding of geomorphic processes (see discussion in Kirkby, 1987).

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